INDIANA DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

In-Situ Thermal Remediation

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Notice

The Technology Evaluation Group (TEG) completed this evaluation of in-situ thermal remediation based on professional expertise and review of items listed in the "References" section of this document. The criteria for performing the evaluation are generally described in the IDEM OLQ technical memorandum, *Submittal Guidance for Evaluation of Remediation Technologies*.

This evaluation does not approve this technology nor does it verify its effectiveness in conditions not identified here. Mention of trade names or commercial products does not constitute endorsement or recommendation by the IDEM for use.

Thermal Remediation: Background and Technology Description

Soil Vapor Extraction (SVE) is a standard remedial technology. A relatively new enhancement is the addition of heat to increase the solubility or vapor pressure of contaminants, facilitating faster and more complete remediation. A significant advantage of thermal remediation is effective removal of non-aqueous phase liquid (NAPL) source zones in soil and groundwater, which can be difficult to accomplish with the traditional technologies currently available. Dissolved and adsorbed contaminants are also reduced to very low levels. Furthermore, thermal remediation can aid removal when the subsurface permeability limits traditional extraction.

Heating enhances remediation thru three pathways:

1. Heating can increase mobility by inducing physical changes, for example decreasing the viscosity or vaporizing the contaminant, etc. Vaporization is the dominant removal method for most chlorinated and volatile contaminants. In general, density, viscosity, surface tension and other physical properties vary somewhat with temperature but vapor pressure and Henry's law constants increase substantially with temperature. Pneumatic or hydraulic extraction must be in place to capture contaminants once they are mobilized. This is the primary method of remediation for most thermal technologies.
2. Heating can enhance chemical reactions by increasing the rate of reaction as temperature rises.

3. Heating can enhance biological reactions by increasing the rate of biological reactions and changing the organisms present.

The primary implementations of the thermal remediation concept are steam enhanced extraction, electrical resistance heating (ERH) and thermal conduction heating (TCH). A brief description of each follows. For most contaminants, increased mobility is the primary remedial enhancement.

Steam Enhanced Extraction

With enhanced steam injection, steam is injected through horizontal or vertical injection wells causing increased pressure gradients and decreased viscosity of the NAPL pushing the oil bank towards extraction wells. This technology has been used in both saturated and unsaturated zones. Additional removal occurs through volatilization, evaporation and steam distillation of volatile and semi-volatile compounds. Liquid phase compounds with boiling points less than water are nearly completely removed while the process is considered effective for liquid hydrocarbons with boiling points up to 175C.

Steam Enhanced Extraction has been used for chlorinated solvents, petroleum and some wood treatment wastes. Permeability must be high enough to allow the steam to permeate. Steam generating capacity from on site operations may make it more cost effective. The combination of electrical heating and steam stripping is termed Dynamic Underground Stripping.

Electrical Resistance Heating (ERH)

In electrical resistance heating, current is passed between electrodes using either six phase or three phase electrical heating; three phase involves a triangular electrode pattern more suited to larger sites and six phase is implemented in a hexagonal pattern more suited to smaller sites since a large network of hexagonal electrodes will have substantial dead zones where current does not flow. Voltage damping is used to reduce voltage at the surface and outside the treatment area for safety.

Electrodes are generally spaced from 8 to 20 ft apart for three phase heating; for six phase heating the hexagon diameter is generally 17 to 40 ft. Resistance to the current flow between electrodes warms the soil and boils a portion of the water. In the area of the electrodes, water may need to be added to ensure conduction. ERH generally requires around two weeks to reach the boiling point of water. The steam generated from the boiling water carries the volatilized contaminants to recovery wells. As water boils away in the most conductive zones, less conductive zones heat up leading to relatively uniform heating; silts and clays are generally more conductive than gravel and sands. Temperatures are the boiling point of the subsurface water which is somewhat contaminant and pressure dependent (as depth increases so will boiling point). Most contaminants are recovered as a vapor instead of being mineralized. ERH has been most widely used to treat VOCs (TCE, PCE, methylene chloride) (USACE, 2009).

Thermal Conduction Heating (TCH) Combined with Vacuum: In-Situ Thermal Desorption (ISTD)

Thermal conduction heating is the application of heat to subsurface soils via conduction. Thermal wells or blankets are used as the heat source. Thermal conductivity is relatively consistent over a wide range of soils leading to uniform heat propagation. Operating temperatures can reach 1400-1500 degrees F. Discrete subsurface layers can be heated by placing conductive heaters at desired intervals; the practical minimum thickness is 8 feet (USACE, 2009).

TCH has been used for PCBs in soil, manufactured gas plant coal tars, pesticide residues chlorinated solvents and creosote contamination. In-situ thermal desorption can incite temperatures high enough to treat semi volatile compounds.

Technology Selection

The physical properties of the contaminant, the geology of the site and the available time frame for cleanup must be evaluated before thermal enhancement is chosen for a site. A US Air Force study (AFCEE, 2005) evaluated 27 sites where thermal remediation was used and found widely inconclusive results on both the cost effectiveness and remedial effectiveness of the technology. If a contaminant has a relatively high vapor pressure, alternate technologies may be just as effective in effecting cleanup. If low permeability limits typical extraction technologies then thermal remediation may increase extraction rates. If a short time frame is required, then thermal remediation may aid in this remedial goal.

At many sites, thermal remediation may only be appropriate in small source areas or for partial cleanup (see remedial goals below). Combinations of systems may be useful if site stratigraphy is varied. For example, steam stripping along with ERH may be used in more permeable areas while ERH alone could be used in less permeable layers of a site.

Remedial Goals and Endpoints

When thermal remediation is used, understanding which processes are occurring is necessary in order to determine appropriate site specific remediation goals. Choosing a remedial goal based on absolute contaminant endpoint concentrations is hindered by the fact that sampling heated media during remediation is difficult and rebound may occur following media cool down; turning systems on and off is expensive. Often, an endpoint based on asymptotic extraction concentrations is chosen. Typical implementation involves measuring contaminant concentrations in recovered vapors and ceasing operations when these concentrations decrease by a predetermined percent (80%) to determine interim concentrations and then a decision is made as to whether to restart the process.

For DNAPL remediation, it is likewise usually best to specify rate of mass removal based on extracted fluid reaching a diminishing return rather than percent mass or volume removal since estimating the volume of DNAPL is difficult. If the goal is only to remove DNAPL, then a concentration indicating no free product may be chosen with the assumption that an alternate technology will be used to close the site. For example, at the Pinellas Environmental Restoration Project (USDOE, 2003) remediation levels were based on concentrations that would indicate the absence of NAPL which meant that the TCE goal to cease operation was 11,000 ug/L. With thermal conduction heating, especially at high temperatures, the remedial goal may be achieving a specified temperature for a minimum period of time. An important consideration in choosing closure criteria is the difficulty in obtaining treatment zone samples during heating (see problems encountered and safety precautions below). For most systems, operational heating generally lasts from 1-3 months.

The specific heat capacity of water (4.21kJ/kg C) is more than four times that of rock or soil (~1 kJ/kg C). To minimize remediation costs it is important to minimize the amount of water to be heated if possible and to impede the flux of groundwater into treatment zones if possible.

System Design and Operation

In situ thermal remediation (ISTR) systems are complex and intricate. Operational design details are best left to experienced contractors. However, a basic design feature is the depth and location of the heated intervals. These intervals must be chosen such that mobilization upon heating occurs in the direction of the contaminant capture system. Hydraulic and pneumatic control should be demonstrated before heating commences. Perimeter and bottom heating prior to sitewide heating is effective at minimizing the risk of contaminants spreading. During steam stripping, cycling subsurface pressure can maximize the mass of contaminants removed; reducing the pressure in the steam zone leaves fluid in that zone slightly superheated leading to enhanced volatilization shortening the remediation time. (USDOE; 2003, Juhlin, 2006)

Operational Monitoring

During operation, subsurface temperature monitoring is required. For heterogeneous sites, thermocouples should be no more than 1.5 m apart vertically and a substantial horizontal monitoring network must be in place. Analysis of system wide parameters during operation can identify dead spots in the remediation network allowing them to be addressed during remediation.

ISTR systems are expensive to operate. Monitoring must be done to ensure that the system is turned off when the benefits of heating are showing diminishing returns and are no longer cost effective. Usually this endpoint should be chosen when site remedial goals are determined. Endpoints may need to be re-evaluated based on actual system data.

Closure Sampling

Drilling into the subsurface to sample during active remediation is possible but creates safety concerns due to the pressure buildup and possibility of steam eruptions. The elevated temperatures mean contaminants are present in multiple phases making accurate concentrations difficult to obtain. See Problems Encountered and Safety Precautions below. Definitive closure samples should be taken after temperatures and saturation have returned to pretreatment levels; if the subsurface is expected to remain heated for an extended period of time, this may not always be practical.

Advantages

- More complete remediation of many recalcitrant contaminants.
- Faster remediation.
- Enhanced bioremediation may occur in areas outside the heated source area due to elevated temperatures.
- Can treat DNAPL in saturated zones and at great depths.
- Areas containing underground utilities and beneath structures can be treated.
- Useful in low permeability silts and clays where typical extraction technologies fail due to low hydraulic conductivity. In particular, TCH is applicable when low conductivity prohibits traditional technologies.

Limitations

- System operating costs, especially electrical costs, are substantial.
- Safety hazards including electrocution, scalding and pressure induced ruptures are more likely than with conventional technologies. Please see safety section.
- Mobilized contaminants may wander off site. Hydraulic and pneumatic control should be demonstrated before commencement of in-situ thermal desorption methods.

Problems Encountered

Vapors condense around unheated extraction wells. Vapor samples drawn from these wells will underestimate concentrations being removed. Likewise, upon sampling, vapors will condense and the concentration in both the liquid and gaseous phase must be known to determine concentrations in the actual extracted vapor.

Confirmatory VOC sampling is hindered by elevated temperatures at the immediate conclusion of operations. VOC losses are inevitable as heat enhances volatilization. Safety precautions are necessary to deal with the extremely high temperatures likely to be encountered. The system must be shut down in advance to dissipate subsurface pressure but the possibility of steam flashing will still exist. Technicians should wear protective clothing and goggles. “Permanent dedicated tubing accessible without opening the well cap should be installed in each well and run through an ice bath before collecting a sample.” (USACE, 2009).

Remedial processes must be understood before implementation. If vaporization is occurring, hydraulic and pneumatic control must be in place. If contaminants are destroyed, end products must be characterized. In one thermal remediation attempt, hexachlorocylcopentadiene, a pesticide precursor, formed pure hydrochloric acid, which destroyed remediation equipment within 10 days (AFCEE, 2005). Contaminants which can be expected to generate low pH waste streams as they volatilize (ex many chlorinated solvents) require corrosive resistant alloys in system components.

Utilities must be delineated and appropriate precautions taken. PVC will melt at the temperatures of some thermal remediation systems. Conductive material cannot be used in the presence of ERH systems.

Safety Issues

The main physical safety issues associated with thermal extraction methods revolve around the fact that electricity is invisible and hot material often has the same appearance as cold material but has the ability to cause severe burns.

As the subsurface is heated, submerged screen monitoring wells can become geysers and erupt upon opening the well. See confirmatory sampling procedures in problems encountered section above for precautions. Since hot vapors and liquids may be encountered, proper PPE is required at all times.

Skilled contractors are required with this technology. OSHA regulations require surface voltage less than 50 Volts but most ERH operates at less than 15V as an added safety measure. Isolation transformers force current to flow only between electrodes. As indicated above, an experienced contractor is required to safely design ERH as well as other thermal remediation systems.

Thermally enhanced SVE systems may incorporate the use of steam to heat soils to be treated. Pressure caused by plugged steam lines may cause a rupture or an explosion in the system. System controls should be in place to monitor the pressure. Likewise pressure buildups in the subsurface can erupt when sampling.

Indiana Case Studies (or use in similar environment)

Only one case study in Indiana is included in the ERH section. Similar environment case studies are outlined below also.

THERMAL CONDUCTIVE HEATING (TCH)

Former Mare Island Naval Shipyard:
Demonstration. September-December 1997: PCBs to a max of 2200mg/kg. Groundwater starts at 15-25 ft below ground surface (bgs) (below target zone). 12 heater vacuum wells drilled to 14 ft bgs were used over a 500 ft^2 area and an additional thermal blanket over an 8x20 ft area to treat soils to 12 in. Average soil temperatures reached 600F. All post treatment samples were non detect for PCBs.

Former Shell Bulk Storage Terminal, Eugene, Oregon*:*
Full Scale remediation of Benzene to 1200 ppb in groundwater; GRO to 35500 ppm in soil and DRO to 9300 ppm in soil. NAPL thicknesswas up to 1m. Treatment over a 40x30 ft area. Soil contamination to 12 ft bgs. The system was composed of 277 heater

vacuum and 484 heater only wells spaced 7 ft apart to a depth of 12 ft bgs. Average in situ temperature reached 540°F during the 120 day heating cycle. LNAPL removed and soil and groundwater concentrations were below risk based concentrations for Oregon. Approximate cost $3Million.

ELECTRICAL RESISTANCE HEATING (ERH)

***KS Bearings. Greensburg, Indiana**:*
TCE/PCE/DCE/Vinyl Chloride. The remedial goal was for the 95% UCL concentration of TCE to be reduced to 13ppm. Subsurface soil was heated from approximately 7 to 28 ft below ground surface. Groundwater was at approximately 17 ft bgs. The system was composed of 133 combination electrode/ collector wells and 28 temperature monitoring locations with multiple depth thermocouples at each location. The maximum subsurface temperature achieved was 114°C during the 204 day heating period. Post treatment sampling indicated remediation met the 95% UCL concentration of 13 ppm TCE.

***Lucent Technologies, Skokie, Illinois**:*
Full scale remediation of TCE. System composed of 107 six phase heating electrodes installed over an acre; 85 were directly through a building floor. Conduction from 11-21 ft bgs which heated interval from 5-24 ft bgs. 37 vapor extraction wells were installed to 5 ft bgs. System was modified to three phase heating after three months. Remediation objective was to reduce concentrations to Tier 3 levels that would allow biodegradation after the system turned off to Tier 1 levels. Concentrations were reduced to less than Tier 3 levels with subsequent biodegradation resulting in less than Tier 1 standards. Cost $1.2 million. $100/cubic yard.

***AveryDennison, Waukegon, Illinois**:*
Full Scale Remediation of Methylene Chloride over a 17000 ft^2 area to a depth of 25 ft. The system was composed of 95 copper electrodes with 34 vapor and steam recovery wells. Remedial goal was to heat the soils to 75°F. Methylene chloride was reduced from a mean concentration of1400 ppm to a mean concentration of 2.51ppm. No cost available.

STEAM ENHANCED EXTRACTION

***Visalia Pole Yard, Visalia, California**:*
Contaminants included creosote, diesel, PAHs, pentachlorophenol (PCP), PAHs. The remedial goal was to remove source contaminants from 3.5 acres at 80 to 100 ft bgs letting natural attenuation occur in the remaining groundwater plume. The system was composed of 11 steam injection wells, 29 ERH wells, and 8 liquid vapor extraction wells. Steam generation was capable of 200,000lb/hr. An estimated1.3 million pounds of contaminants were removed. Groundwater PCP concentrations decreased two orders of magnitude. Total Cost $22.5 Million or $197/cubic yard.

Conclusion

Thermal extraction is a viable technology which can facilitate and/or expedite cleanup at many contaminated sites. The increased energy costs and safety costs must be considered when choosing this technology. This technology may be appropriate at sites where traditional extraction technologies fail. Hydraulic and pneumatic control of the site must be established before heating. Remediation endpoints appropriate for the technology must be chosen.

Further Information

If you have any additional information regarding this technology or any questions about the evaluation, please contact Susan Horein, Environmental Engineer at (317) 234-4155 or by e-mail at shorein@idem.in.gov. This technical guidance document will be updated periodically or if new information is acquired.

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